High Fluence, High Beam Quality Q-Switched Nd:YAG Laser with Optoflex Delivery System for Treating Benign Pigmented Lesions and Tattoos

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ABSTRACT

Q-switched neodymium (Nd:YAG) lasers are very effective in the treatment of benign pigmented lesions and tattoos. For effective and safe clearance or eradication of pigments an Nd:YAG laser system must be able to deliver nanosecond pulses with a very high pulse energy, and a uniform beam profile. However, a host of technical challenges are associated with Q-switched Nd:YAG lasers which are capable of sufficiently high energies at short, nanosecond laser pulses. The optical components of a Q-switched laser are exposed to extremely high (several hundred MW) powers that are very close to, or above, their damage thresholds. In addition, high powers may lead to optical breakdown and plasma formation in the air, thereby reducing transmission and deforming the beam. For these reasons, some commercially available devices use a rapid sequence of two, or more, low power laser pulses, instead of a single giant pulse, to increase the total delivered laser fluence to the treated tissue without increasing the instantaneous laser pulse power. In this paper, we report on a study in which the efficacy of pigment clearance by a single giant pulse was compared to the efficacy of clearance under multiple pulse conditions. Results are presented that show that multiple pulsing is not effective, and that high-power, single pulses are mandatory for effective pigment removal. Further, a novel laser delivery approach is described that enables reliable delivery of giant laser pulses with very high beam quality.

Key words: laser pigment treatments; Q-switched laser; Nd:YAG laser; KTP laser; Optoflex, tattoo removal lasers.

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I. INTRODUCTION

Extremely short pulse, Q-switched (QS) laser systems can successfully lighten or eradicate a variety of pigmented lesions. Pigmented lesions that are treatable include freckles and birthmarks including some congenital melanocytic naevi, blue naevi, naevi of Ota/Ito and Becker naevi.[1-11]

The QS laser systems can also selectively destroy tattoo pigment without causing much damage to the surrounding skin.[12-15] The altered pigment is then removed from the skin by scavenging white blood cells and tissue macrophages.

Q-switching, sometimes known as giant pulse formation, is a technique by which a laser can be made to produce a pulsed output beam.[16] The technique allows the production of light pulses with extremely short (on the order of nanoseconds) pulse duration and high (megawatt) peak power, much higher than can be produced by the same laser operating in continuous wave mode (constant output), or Variable Square Pulse (0.1-300 ms) mode. [17-20]

The high power, short pulse QS laser systems are effective because they confine their energy to the treated pigments. The time duration (pulse duration) of the QS laser energy is so short that the extremely small pigments of 10-100 nm size are heated to fragmentation temperature before their heat can dissipate to the surrounding skin. This prevents heating of the surrounding tissue that could potentially lead to burns or scars.

The most likely cause of pigment destruction under QS laser pulses are shockwave and/or cavitation damage, the photomechanical physical effects produced from thermal expansion, and/or the extreme temperature gradients created within the melanosome or tattoo pigment. Melanin absorbs and localizes the high-intensity irradiation from Q-switched lasers, thereby creating a sharp temperature gradient between the melanosome and surrounding structures. This gradient leads to thermal expansion and the generation and propagation of acoustic waves, which mechanically damage the melanosome-laden cells.

For the selective removal of pigment the color of the laser light must penetrate far enough into the skin to reach the target pigment, and must be highly absorbed by the pigment relative to the surrounding skin. Different pigments therefore require different laser colors. For example, red light is highly absorbed by green tattoo pigments.

In current practice, numerous lasers can specifically target pigmented lesions, including red-light lasers (eg, 694-nm ruby, 755-nm alexandrite), green-light lasers (eg, 532-nm frequency-doubled Nd:YAG), and near-infrared lasers (eg, 1064 nm Nd:YAG). The wide range of lasers that can be used to treat pigment is a result of the broad absorption spectrum of melanin (Fig. 1). [17, 21]

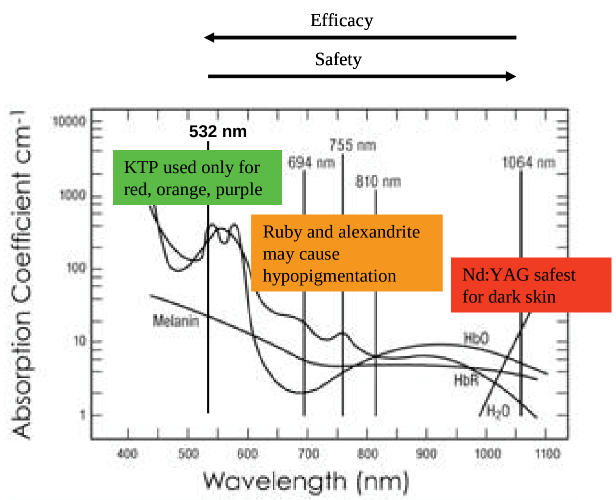

Fig. 1: Absorption characteristics of the various skin structures. [17, 21] The 1064 nm wavelength lies at the skin's "optical window".

Superficially located pigment is best treated with shorter wavelength lasers whilst removal of deeper pigment requires longer wavelength lasers that penetrate to greater tissue depths (Fig. 2). For example, green-light (KTP) lasers do not penetrate as deeply into the skin as the red-light and near-infrared lasers, owing to their shorter wavelengths. Therefore, green-light lasers are effective only in the treatment of epidermal pigmented lesions. Caution is needed when treating darker-skinned people as permanent hypopigmentation and depigmentation may occur.

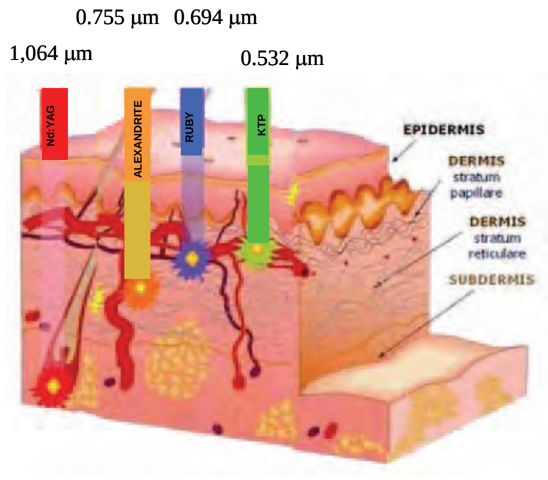

Fig. 2: Schematic representation of penetration depths of different Q-switched lasers.

Q-switched Nd:YAG lasers produce a 1064 nm wavelength beam with a pulse duration of 5 -15 nanoseconds. Although this wavelength is not absorbed as well by melanin as green- and red-light wavelengths are, its advantage lies in its ability to penetrate more deeply into the skin (up to 4-6 mm). A laser which produces 1064 nm wavelength light is also more useful in the treatment of lesions for individuals with darker skin tones.

The Nd:YAG laser rod is insensitive to temperature changes resulting in very stable and reliable laser operation. By contrast, ruby and alexandrite laser rods contain Cr^{3+} ions, and are therefore very sensitive to thermal and pumping nonhomogeneities. This may result in the unstable operation of these lasers. [31] Also, ruby lasers have to be cooled down to sub-room temperatures, and alexandrite lasers need to be heated up to high temperatures before the lasers can be operated.

In addition, the infared wavelength light produced by a Q-switched Nd:YAG laser system can be converted into visible wavelength light, making this type of system the safest and most versatile pigment treating laser available. The latest devices incorporate an Nd:YAG (1064 nm) laser as the main laser source from which all other wavelengths are generated (see Fig. 3). The first wavelength converter is KTP crystal, which has the ability to double the frequency of incoming Nd:YAG beam and thus produce the halved wavelength of 532 nm (green light).

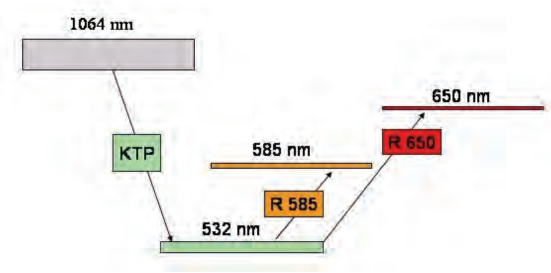

Fig.3 Wavelength conversion diagram

For further wavelength conversions to 585 nm (yellow) and 650 nm (red) the KTP 532 nm laser beam is used as a source for optical pumping of solid dye laser handpieces (see Fig. 4).

Fig. 4: Example of 585 and 650 nm lasers (R585 and R650, manufactured by Fotona d.d.) that can be pumped by a KTP (532 nm) laser.

These particular four wavelengths (1064, 532, 585 and 650 nm) are optimally spaced to cover the whole spectrum of color (Fig. 5).

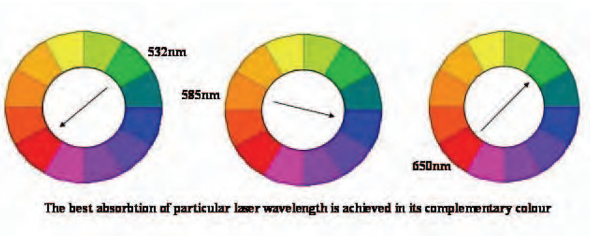

Fig. 5: Diagram of complementary colors.

The Nd:YAG (1064 nm) wavelength is in the near-infrared part of spectrum it is not presented on complementary colors diagram on Fig.5, but it is best absorbed in dark colors (black, dark blue, brown) and is the gold standard for the removal of these tattoo colors, as well as most pigmented lesions. The other three wavelengths cover lighter colors: 532 nm (green laser light) treats red and neighboring reddish and tan tones, 585 nm (yellow/orange laser light) treats blue, sky blue and neighboring bluish tones and 650 nm (red laser light) treats green and neighboring greenish tones (Fig. 6).

Pigment color	Wavelength
Black, Brown, Dark Blue	1064 nm
Red, Orange, Purple	532 nm
Sky Blue	585 nm
Green	650 nm 694 nm (ruby) 755 nm (alex)

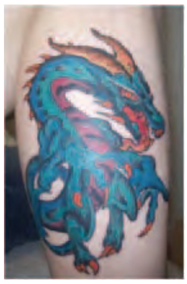

Fig. 6: Relation between pigment color and corresponding treatment wavelength.

In addition to the appropriate choice of laser color, a laser system must be able to deliver nanosecond pulses with a very high pulse energy, and a uniform beam profile. The fluence (F) is one of the main settings for treating pigments. It is defined as energy density:

$$F = E/A \qquad (1)$$

Where E is the energy of the laser pulse and A is the spot size area, $A = \pi d^2/4$, of the laser beam at the skin surface. Sufficient laser fluence must be delivered during each laser pulse to heat the pigment to fragmentation. If the fluence is too low, the pigment will not fragment and no removal will take place.

The fluence can be increased by the reduction of the laser beam to a smaller spot size area. However, this results in a longer treatment time. More importantly, the effective treatment fluence is reduced at smaller spot sizes. As a beam propagates into the skin, light scattering by the skin spreads the beam radially outward on each side, which decreases the beam's effective fluence as it penetrates into the skin. This effect is more pronounced in smaller spotsizes where the spreading of the beam is relatively large compared to the incoming beam spot size (See Fig. 7).

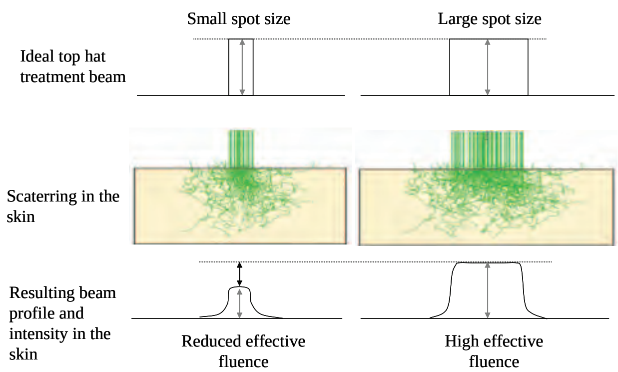

Fig. 7: Influence of scattering on the effective laser beam spotsize. The beam spreads radially outward on each side by approximately Δr = 0.7 mm. The effect is relatively less significant at larger spot sizes. [17]

Note that the the scattering coefficients of epidermis and dermis decrease with wavelength in the visible and near-IR parts of the spectrum (see Fig. 8), again favoring use of the Nd:YAG laser wavelength. [17, 21]

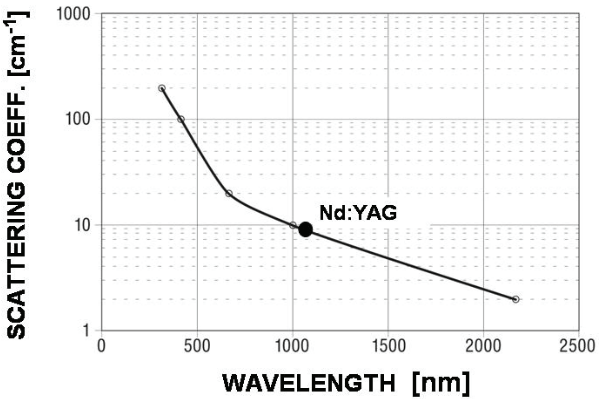

Fig. 8: A log plot of the scattering coefficient for skin as a function of wavelength.[17, 21] Note that the scattering effect decreases with increasing wavelength. The Nd:YAG (1064 nm) laser has a low scattering coefficient and is thus less affected by the scattering than the ruby (694 nm) or alexandrite (755 nm) laser wavelengths, which are also used in pigment removal treatments.

Figure 9 shows the dependence of the effective flluence on the skin surface on Nd:YAG (1064 nm) laser spot size.

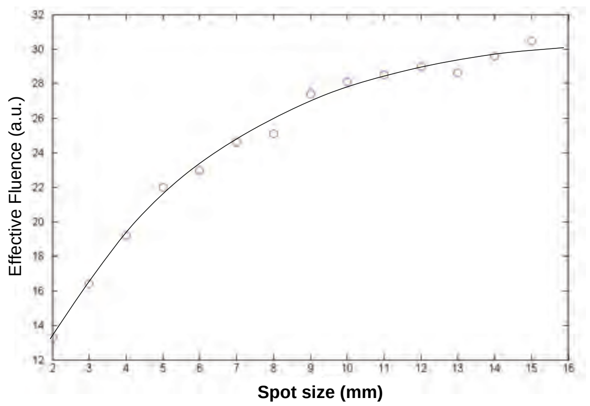

Fig. 9: Computer simulated dependence of the effective fluence on the laser spot size. The effective fluences at different spot sizes are calculated for the same incoming laser beam fluence. The line is provided as a visual aid. [17]

This is why the effective fluence within the skin of, for example, a 2 mm incoming laser beam is approximately two times smaller than the effective fluence of an 8 mm laser beam. This results in approximately two times lower treatment efficacy when using a 2 mm spot size beam compared to an 8mm spot size beam. When the incoming laser fluence is the same for both spot sizes, the resulting effective fluence is lower not only on the surface but also within the skin.

Based on the above, larger spot sizes enable deeper penetration and more effective treatment of pigments. Better beam profiles also minimize epidermal damage and decrease bleeding, tissue splatter, and transient textural changes.

Of course, the practitioner can treat pigments with smaller beam spot sizes if the laser fluence is adjusted accordingly. For example, if the incoming fluence of a 2 mm laser beam is increased by a factor of two, the penetration and the treatment efficacy resulting from 2 mm and 8 mm laser beams become similar. This technique is successfuly employed for Variable Square Pulse (VSP) skin rejuvenation and hair removal treatments since VSP lasers are capable of generating sufficiently high laser pulse energies in the millisecond pulse duration range. [17] However, this is often not a viable strategy for Q-switched lasers where high laser energies within extremely short, nanosecond pulses are difficult to obtain.

Not all commercially available Q-switched Nd:YAG lasers are capable of delivering sufficiently high energies at short, nanosecond laser pulses. Extremely high laser powers may damage laser optics and cause optical breakdown in the air. For this reason, some commercially available devices use a rapid sequence of two or more lower power laser pulses, [22] instead of a single giant pulse, to increase the total delivered laser fluence to the treated tissue (Fig. 10).

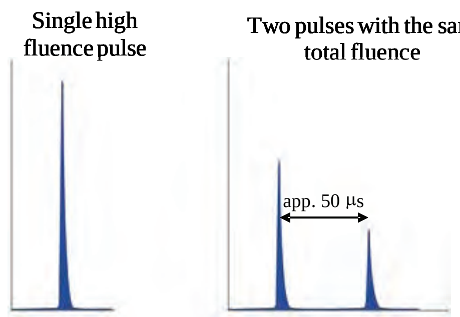

Fig. 10: Energy can be delivered to the tissue with a single giant pulse or with two or more pulses with the same cumulative energy.

However, applying a sequence of smaller laser pulses may not be as effective as using a single large pulse. First, smaller laser pulses may be below the laser power threshold for pigment removal, and thus achieve no pigment claearance. Second, tissue characteristics change following the irradiation with a laser pulse. This may reduce the pigment removal efficacy of subsequent laser pulses.

Here, we report on a comparative study of the efficacy of pigment clearance under single giant pulse and multiple pulse conditions. In the study, tattooed pig skin was subjected to an irradiation of a single Nd:YAG (1064 nm) laser pulse, or alternatively to a sequence of four consecutive Nd:YAG laser pulses with the same cumulative fluence. Results are presented that show that the multiple pulsing approcah is not effective, and that single high power pulses are mandatory for effective pigment removal.

In addition to high single pulse energy, the homogeneity of laser beam profile is of great importance in pigment removal laser systems. A homogeneous beam profile provides safety in treatment as it enables even distribution of energy across the treated area. Better beam profiles minimize epidermal damage and decrease bleeding, tissue splatter, and transient textural changes in the skin. However, due to the non-linearity of the Q-switched lasers, achieving homogeneous beam profiles has been a serious challenge for the laser industry. In this study, we experimentally tested the latest Optoflex® technology that has been developed to achieve an almost perfect homogeneity of the beam profile. [23,24]

II. MATERIALS AND METHODS

a) Comparative study of pigment clearance

Comparative study of the efficacy of single giant pulse and multiple pulses in pigment treatments was carried in-vitro on tattoed pig skin.

Tattoo dots from two selected segments (Fig. 11) of tattooed pig skin (ears) were treated with a total fluences of 3,6 J/cm², either delivered within a single 1064 nm pulse or within a sequence of four consecutive 1064 nm pulses separated by 65 μsec, and each having a fluence of 0,9 J/cm² (resulting in a total cumulative fluence of 3.6 J/cm²). The fluence of 0.9 J/cm² was above the tattoo pigment clearance threshold.

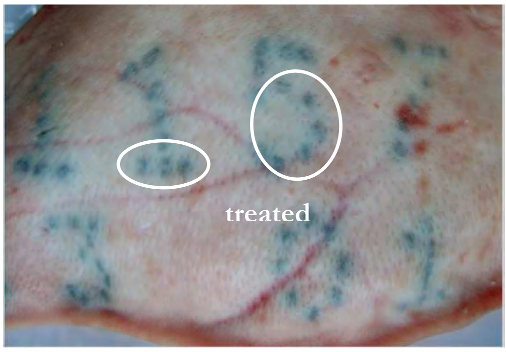

Fig. 11: Sample of tattooed pig's skin

b) Optoflex Laser Delivery System

In technical, and particularly medical, applications, the transmission of a laser beam from a laser source to a target location is realized by a flexible light guide or along an optical path within an articulated arm. In high-power lasers, the articulated arm is the preferred delivery method for a number of reasons. Fibers cannot withstand high optical power densities. When focusing a high power laser beam into a fiber, optical breakdown can occur before the beam reaches the fiber. In addition, unwanted nonlinear optical effects occur in fibers.

In our experiment, the Nd:YAG Q-switched laser employed a variable reflectivity technology in combination with the unstable resonator concept. The main characteristics of the beam emerging from such a laser are exceptional uniformity of the near-field beam profile and very low beam divergence so that, in this way, diffraction-limited conditions are approached. However, due to diffraction effects the beam changes its profile considerably while propagating along the length of the articulated arm, which is used for the delivery of the beam to the target area. In addition, due to the high quality of the beam any change in laser resonator conditions, in particular variations related to the laser rod lensing due to different pumping conditions, result in accentuated variations of the beam further from the laser output. It is not only that the beam diameter is influenced in this way, but also that the beam profile quality deteriorates in comparison with highly desired near-field top hat conditions, which is usually unacceptable for the application.

In order to analyse the effects of beam diffraction, we have simulated the beam spread along this distance for a given beam diameter and a given laser wavelength. For the 10 mm diameter Nd:YAG laser beam with the initial top hat profile we get the following beam profile (Fig. 12), shown as the intensity distribution.

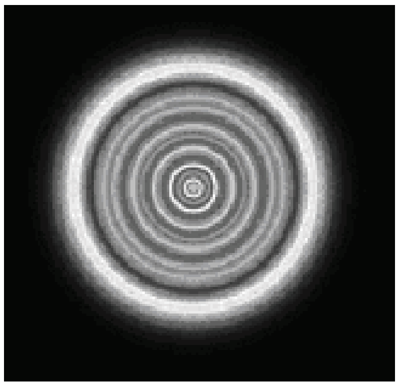

Fig. 12: Diffraction distorted beam profile of a 10 mm top hat beam after propagating through a standard articulated arm (assumed length of 2.2 m).

We can see that the previously flat profile has developed concentric ripples with a considerable modulation.

In order to avoid diffraction phenomena, and to achieve stability of the treatment beam under a wide range of laser output parametrers, a novel, Optoflex® technology was developed that prevents beam deterioration by combining the technique of relay imaging with vacuum optical cell technology (Fig. 13).[23] Optoflex® technology turns away from the conventional beam guiding concept, in which a beam diameter as large as possible is maintained along the entire optical path for reducing power density. The arrangement of a focus-like crossing area in the laser beam is made that enables a configuration of the optical arrangement with exact imaging quality.

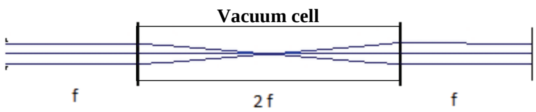

Fig. 13: Relay imaging involves focusing of the laser beam within its optical path to the treatment area.

Within the new concept, the diffraction phenomena can be avoided almost completely. In the crossing area the laser beam has a waist-like constriction with increased power density. In addition, because with the Optoflex® technology this area is located within the optical vacuumized cell, ionization or plasma generation is reliably prevented. A deterioration of the optical transmission or even an optical breakdown can be excluded even at high power density, because the increased energy threshold of the gas fill within the optical cell reliably prevents ionization or plasma generation.

As a result, the wavefront is propagated virtually without degradation almost to the end of the articulated arm. The calculated beam profile at the exit of the Optoflex® technology arm is shown again in Fig. 14. Considerable improvement can be observed.

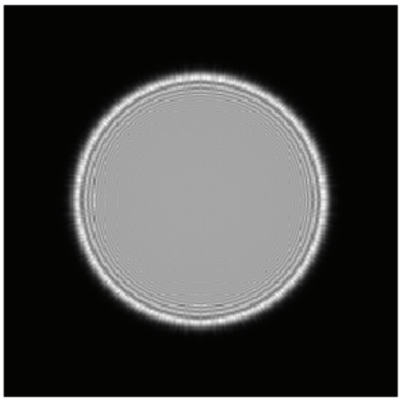

Fig. 14: High quality beam profile of a 10 mm top hat beam after propagating through an Optoflex® articulated arm (assumed length of 2.2 m).

The experimental arrangement of the Optoflex® delivery system used in our experiment is shown in Fig. 15, and is described in more detail in [23].

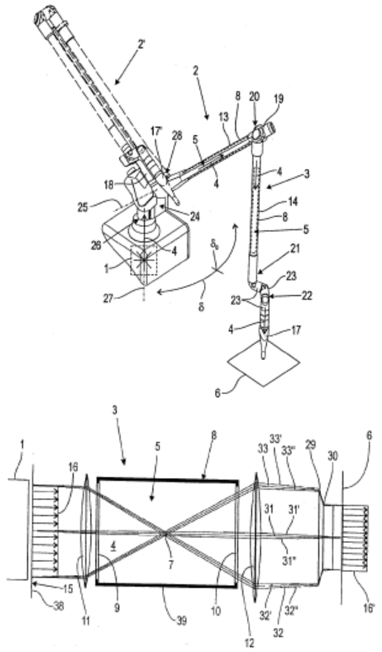

Fig. 15: Schematics of the Optoflex® technology experimental arrangement. [23]

III. RESULTS

a) Comparative study

Figure 16 shows the pigment clearance immediately following an irradiation with a sequence of four consecutive pulses (dots A), and a single laser pulse (dots C). Dots B represent the control area that was not irradiated.

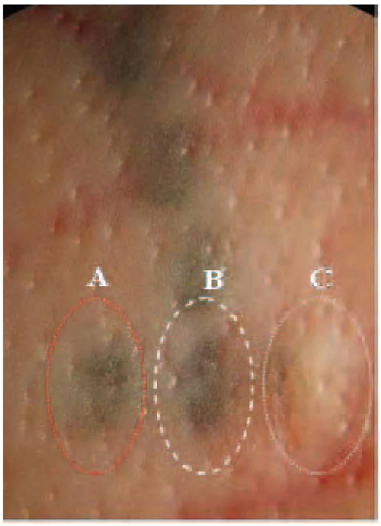

Fig. 16: Results of pigment clearance where tattoo dots B represent non-treated dots, tattoo dots A were treated with multiple pulses, and tattoo dots C with single pulse of equal fluence.

Similarly, Fig. 17 shows the difference in the effect of a single (C) and multiple (A) laser pulses, always with the same total laser fluence, on a tattooed pig's skin.

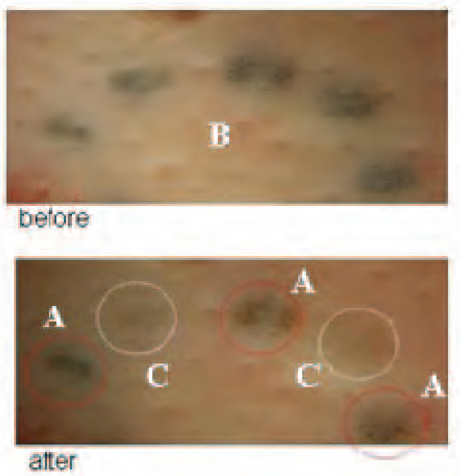

Fig. 17: Results of pigment clearance where tattoo dots B represent the pigment dots before treatment, tattoo dots A were treated with multiple pulses, and tattoo dots C with single pulse of equal fluence.

From both cases presented, it is clearly visible that multiple pulses cannot achieve the same result as one strong single pulse. These results are in agreement with previous publications, and can be explained by the mechanism of laser pigment removal.

b) Optoflex Laser Delivery System

Figure 18 shows a measured laser pulse profile as obtained from the Q-switched Nd:YAG laser system with the Optoflex® delivery (Fig. 19).

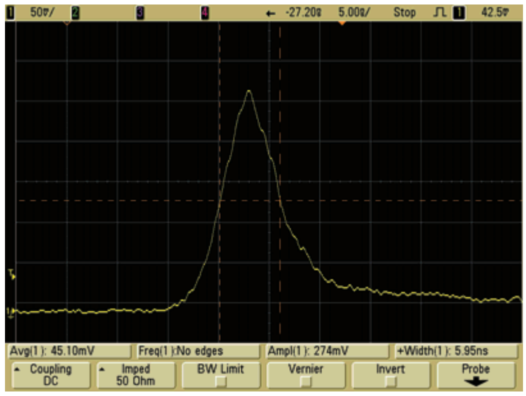

Fig. 18: A 6 ns laser pulse with a single laser pulse energy of 1.6 J, resulting in a single laser pulse power of 267 MW, as measured at an output of a Fotona QX Max laser system.

Fig. 19: Q-switched Nd:YAG laser system with Optoflex® laser delivery technology (QX Max, manufactured by Fotona d.d.). [25]

The resulting maximum achievable fluences are above 15 J/cm² at 1064 nm, and above 7.5 J/cm² at 532 nm (see Fig. 20).

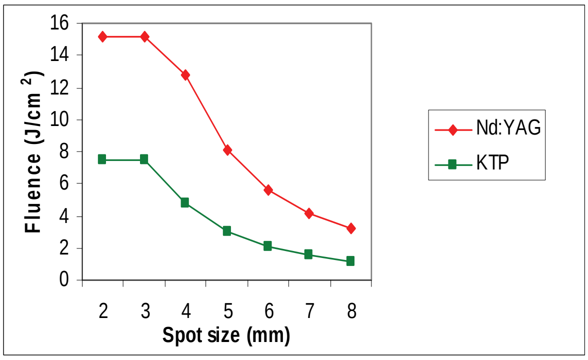

Fig. 20: Maximum laser fluences achievable at different spot sizes.

Experimentally measured beam profile at the treatment site is shown in Fig. 21.

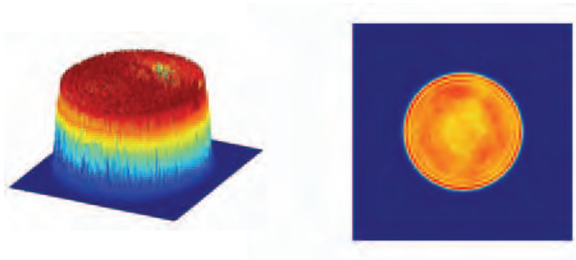

Fig. 21: Experimentally obtained laser beam profile at the position of the treatment site.

IV. DISCUSSION

The mechanism of action of the laser pigment reduction is through photon absorption by the pigment. During a 5-15 nanosecond pulse, temperatures can exceed 1000°C. The gaseous products of pyrolysis and pores created by superheated steam, account for the immediate whitening of the treated skin (see Fig. 22).

Fig. 22: Example of immediate whitening of treated tattoo

An optical shield is formed that prevents any subsequent laser pulses from reaching the remaining, deep pigments (as shown in Fig. 23).

Fig. 23: Whitening results in an optical shield that prevents subsequent pulses from reaching the remaining underlying pigments.

Typical clinical cases of treatments with the high beam quality, high single pulse power Q-switched Nd:YAG laser are depicted in Figs. 24- 28.

Fig. 24: Treatment of Nevus of Ota. [26]

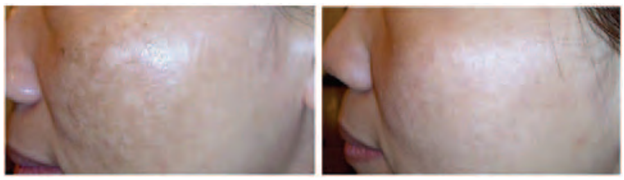

Fig. 25: Treatment of skin color and texture. [27]

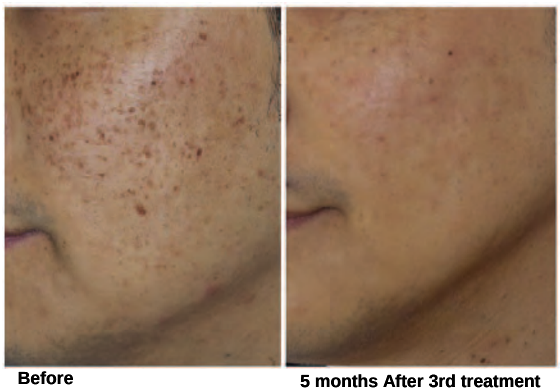

Fig. 26: Treatment of ephelides. [28]

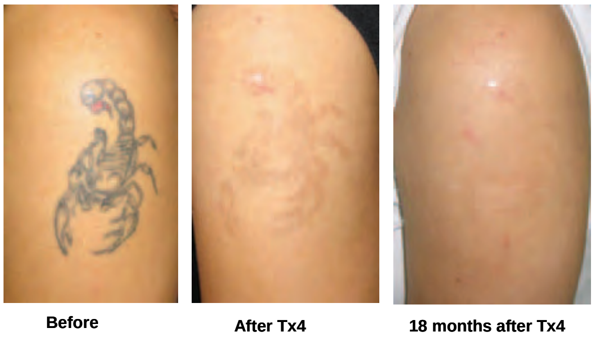

Fig. 27: Removal of tattoos. [29]

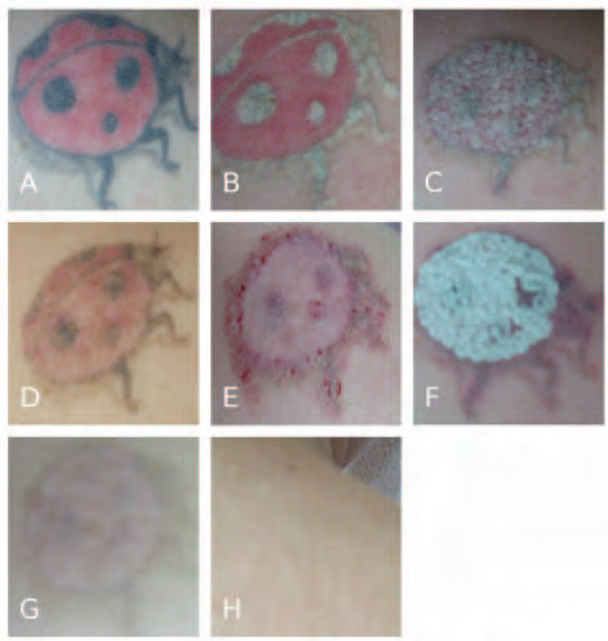

Fig. 28: A lady bug tattoo was removed across 4 treatment sessions. (A) Before Session 1 (B) After the Nd:YAG pass in session 1 (C) After the KTP pass session 1 (D) Before Session 3 (E) After the Nd:YAG pass in session 3 (F) After the KTP pass in session 3 (G) After 4 treatment sessions (already recovered (H) 8 months after. [30]

V. CONCLUSIONS

Because of optical shielding, applying a sequence of laser pulses to the treated tissue in order to increase the delivered laser fluence and thus the speed of treatment is not effective. Rather, it is necessary to treat the skin area with appropriately high single laser pulse fluence, and if necessary to repeat the treatment after the whitening has disappeared.

The latest variable reflectivity unstable resonator Q-switched Nd:YAG lasers, combined with the vacuum cell Optoflex® technology delivery arm are capable of delivering high single pulse energies, with homogeneous top hat beam profiles at the treatment site.

High energy single pulses are not only important for safe and effective pigment treatments, but also for the effective wavelength conversions of the 1064 nm infrared wavelength to the green (532 nm), yellow (585 nm) and red (650 nm) color wavelengths. The Q-switched Nd:YAG medical laser thus provides an ideal combination for treating pigments and tattoos: from superficial to deep lying pigments, from black, brown and blue to red, orange, purple, and from the least absorbent to most absorbent pigments.

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